LONG LIFE SPARKER FOR PULSE POWERED UNDERWATER ACOUSTIC TRANSDUCER

L. H. Fry, P. Adair, Jr., R. Williams
U. S. Navy Coastal Systems Station, 6703 W. Highway 98
Panama City, FL 32407-7001

Abstract

A long life underwater sparker has been developed by the US Navy as part of a pulse powered acoustic generator for minesweeping applications. This sparker has demonstrated continuous operation for more than one and a half hours at one kiloJoule discharge per pulse at a 10 Hertz rate. Additionally, the sparker was operated at one half kiloJoule discharges (10 Hertz) for more than two and a half hours. These operations were in a saltwater environment from a prototype high speed demonstration platform. This sparker design utilizes a coaxial configuration and is fabricated with off-the-shelf components and materials. In general, fabrication requires minimal facilities with the exception of the insulation between the anode (center rod) and the cathode (outer cylinder) which was fabricated by Amalga Composites Inc. with a proprietary process that utilizes cyclo-aliphatic compounds for the resin. The sparker is sacrificial which means the lifetime is dependent on the length of the sparker. The efficiency (electrical to acoustic), which depends on the specific configuration of the companion pulse power system, ranged from 6% for one kiloJoule discharge to 3% for one half kiloJoule discharges. The lifetime of the current design was dictated by the test requirements and could easily be extended. The sparker can be quickly changed out and the mounting component can be recycled. The advantages of this design are: simplicity of design, low fabrication cost (~$70/sparker), seawater operation, relatively high efficiency and low hydrodynamic drag.

I. INTRODUCTION

In the early 1990s the Navy identified the need to develop a new minesweeping system that will fit on a small, high speed, remote/autonomous, surface platform. The Advanced Lightweight Influence Sweep System (ALISS) program was organized to develop such a system. (Influence minesweeping systems typically employ acoustic and magnetic signal generators.) The acoustic technology chosen for this effort was a pulse powered sparker where bursts of electrical current are discharged by a sparker device in the water. In the water this discharge produces a bubble much like a chemical explosive or air gun. The noise is generated primarily by the large pressure pulses emanating from the expansion and collapse of the bubble. The choice of the spark gap was driven by the need for low in-water drag (high speed requirement), relatively good efficiency at low frequencies and some capability to change the acoustic output to emulate a specific craft signature. While underwater discharges have been under investigation for several decades, most of the work involved single shot laboratory systems or systems that fire a burst of shorts over a relatively short period of time (few seconds). The driving requirement for the Navy is the sparker be capable of operating over extended periods of time (tens of minutes to hours) without having to stop operation for adjustment or replacement. Additionally, the operation of the system (acoustic output) had to be relatively consistent from spark to spark or from one group of sparks to another, the sparker had to be small in size to minimize drag and the sparker had to be relatively cheap to fabricate and easily installed. Currently the greatest use of underwater sparkers in a repetitive mode is in lithotripsy (a commercial medical application). Typically these sparkers only last a few hundred shots (less that a minute in the minesweeping application) and are at much lower energies. In the 1960's several underwater sparkers were developed for the oil exploration industry. These systems generally operated at a repetition rate almost 40 to 60 times less that that require by the Navy. The efficiency of these systems varied. One system with the best efficiency used a wire initiated discharge system which involved feeding a small gauge wire across a pair of electrodes. Electric current then passed through the wire causing it to vaporize and created the plasma for the discharge. The other system used a single electrode which created a 'corona" discharge at the tip of the electrode as current passed from the electrode to the salt water (which acted as the negative electrode). The efficiency of this system was typically poor but was compensated for by using large discharge energies.

II. ALISS DEVELOPMENT

In this effort, early attempts by different groups at developing a long life sparker focussed on point to point electrodes (electrodes facing each other on an axis going through their centerline) coupled to spiker/sustainer pulse power systems. The spiker/sustainer concept involves a sub-circuit that imposes a fast rising, high voltage pulse (usually 100 kVolts) across the gap to breakdown the medium between the gap and then switching in a lower voltage (usually 3 kVolts) to drive current through the plasma and generate the bubble. The idea was that the spiker was more efficient at creating the plasma and the low voltage pulse was more efficient at putting energy into the plasma to create the bubble. These efforts had limited success and had low efficiencies in saltwater

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environments (the first system actually would not operate in salt water) while requiring large in-water bodies to contain the sparkers. Furthermore the sparkers had short lifetimes ranging from a few hundred shots to a few thousand shots. After reorganizing the acoustic effort it was decided to re-examine earlier systems especially those from the oil exploration industry and review new data that was forth coming from work that was being done at the University of Texas/APL[1]. Additionally, data from the previous efforts showed that the spiker was of little benefit to the system and in fact the spiker/sustainer systems had less efficiency than a "sustainer only" system for saltwater operation. The breakdown process at the lower voltages of the sustainer is probably a "thermal" process. In this mode a vapor bubble forms between the electrodes due to heating in the medium caused by the initial surge of current in the gap. The lower density of the vapor facilitates the breakdown process since the dielectric strength of the vapor significantly less than that of the liquid.[2] After experimenting with different concepts such as sparkers that use wire initiation and air feed to facilitate breakdown, single electrode "corona" sparkers, and parallel electrode sparker configurations, it was decide to focus on developing a coaxial sparker similar to the one used by UT/APL and others. Furthermore, the spiker was dropped from the pulsed power subsystem thus greatly simplifying that system and reducing its size and weight. The coaxial configuration was chosen because it allows the sparker to erode or "burn" down in a controlled fashion such that the anode exposure and spacing between the electrodes is approximately constant. The performance of the sparker is highly dependent on the exposure of the anode and the gap spacing since the current can become too diffused to efficiently breakdown the medium for large anode areas and gap spacings. The challenge was to find the right combination of electrode and insulator materials that would erode at a reasonable rate while maintaining the optimum configuration. A critical element in the development of the sparker has been finding the best insulation material. Insulation materials tend to be susceptible to the extreme shocks from the bubble expansion and collapse and tend to erode much faster than the metal electrodes. The sparker design has also evolved in various other ways to deal with the high stresses imposed on the sparker structure due to the repetitive expansions and collapses of the bubbles generated by the discharges.

III. DESCRIPTION

A cross-sectional view of the sparker/collar assembly is shown in Figure 1. The primary components of the sparker are the anode (center electrode rod operated at a positive charge), the cathode (outer cylindrical electrode operated at a negative charge) and the insulation between the anode and cathode. The anode is a 25" diameter rod made of a composite metal material with a composition of 70% copper and 30% tungsten (by weight). The cathode

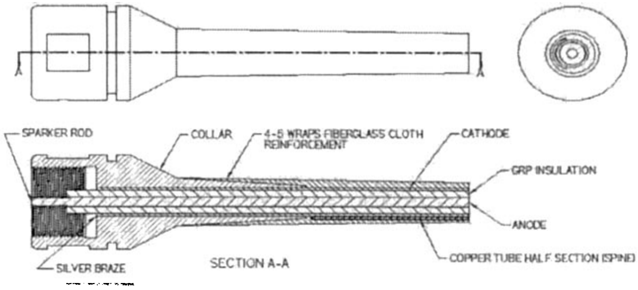

Figure 1. Cross sectional view of sparker assembly.

is standard alloy 122 copper tubing (99.90% copper and .02% phosphorous) with an outer diameter of .75 inches and a .065 inch wall thickness. The insulation is a glass reinforced epoxy composite material that is proprietary to Amalga Composites Inc. During assembly the cathode tube is inserted in the collar and silver soldered at the top of the cathode to the collar (inside). The anode+insulation rod is then epoxied into place inside the cathode. The sparker/collar assembly is further reinforced with a half section of copper tubing epoxied on the aft side of the cathode. Epoxy/fiberglass cloth material is then applied to the exterior of the sparker (over the cathode and part of the collar). The collar provides a rigid structure to mount the sparker on and enables the sparker to be connected to the current carrying structures that connect to the power lines on the deck of the boat.

Figure 2 shows the sparker assembly mounted in the stand pipe structure. The collar/electrodes (sparker) assembly is attached to the anode connector (.5 inch diameter copper rod) and the cathode connector (1.5 inch copper pipe) that brings the electrical power down to the sparker from the power cables on the deck. This whole assembly is then mounted in the stand pipe structure that connects the deck with the bottom of the boat.

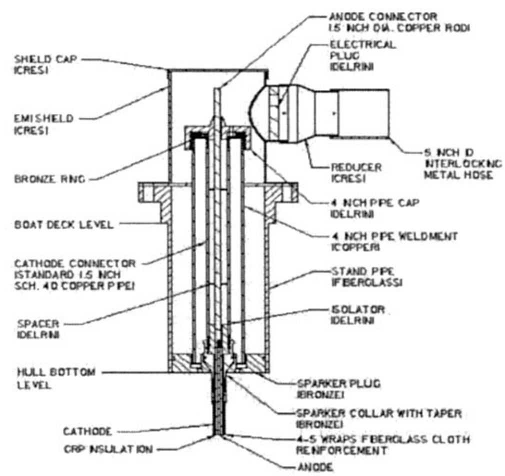

Figure 2. Cross-section view of sparker assembly mounted in standpipe structure.

During the discharge electrical current passes from the anode to the cathode where they are exposed to the water (end of sparker) causing the water in the region of the arc to vaporized and form an rapidly expanding bubble.

Figure 3 shows the pressure profile of a typical underwater spark gap discharge. The pressures in the bubble during the discharge are extremely high. After the discharge stops the bubble will continue to expand until it reaches its maximum size (much larger than the original volume) at which point the pressure in the bubble is considerably less than the ambient pressure of water around it. The bubble will then begin to collapse and return to near its original size during the discharge. The pressure in the bubble at collapse is typically equal to and often much more than the pressure during expansion. These intense, short duration pulses (expansion and collapse) produce most of the sound emanating from the bubble and also cause most of the erosion to the sparker.

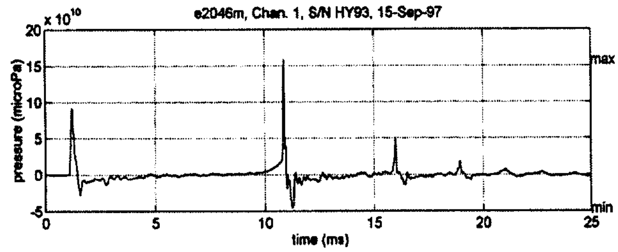

Figure 3. Pressure profile from underwater spark gap

IV. DESIGN CONSIDERATIONS

As mentioned in the text above, the advantage of the coaxial sparker configuration is the potential to maintain a minimum anode exposure and constant gap spacing between the anode and cathode. To do this the erosion of the anode and cathode must be approximately the same. Additionally, the devices need to be produced at reasonable costs. Thus, as much a possible, the use of commercially available materials was emphasized. The materials for the anode and cathode as well as their dimensions were determined by experimenting with commercially available parts. The anode rods are available from a number of suppliers and are normally used in industry for electro-discharge machining. These rods are manufactured by compressing the mixture of copper and tungsten granules at high pressures and sintering them at a temperature above the melting point of copper. The resulting material has been found to give a good combination of hardness for erosion resistance and good conductivity for maximum energy transfer.

In the case of the insulation the erosion is typically well localized and can shatter not only hard, brittle materials like ceramics but also tough but pliable materials like TEFLON. This localized erosion can also create a hot spot on the surface of the insulation that will precipitate the next discharge. The continuation of this trend will cause the erosion to "tunnel" into the insulation and eventually cause the performance of the sparker to prematurely deteriorate and/or destroy a large section of the sparker. To resolve this problem the insulation needs to erode with axial uniformity. Experiments have shown that this can be achieved by using glass fiber reinforced epoxy materials with the fiber mostly axially wound. In the Amalga process a cyclo-aliphatic compound has been added to the epoxy to enhance the ability of the composite to hold off voltage breakdown (dielectric constant) and give additional heat resistance. The reinforcement is an electric grade glass fiber strands that are wetted with the epoxy and applied by winding the strands on the anode rod at maximum tension to give maximum glass content to the composite (~75-80%). This composite is given further lateral and longitudinal strength by adding several layers of a Nexis polyester cloth at different insulation thicknesses during the winding process. This was done to prevent the insulation from breaking off and coming out of the sparker in sections during the discharge process.

The cathode tube specification was determined by trying the various sizes of commercially available stock. While the sparker is firing, the length of the cathode does not necessary have to exactly match that of the insulation and anode. If the erosion of the anode and insulation are closely matched, the electrical gap of the sparker will remain approximately the same during the operation of the sparker. The tubing does have to be rugged enough to withstand the tremendous forces exerted on it by the expansion and collapse. When the sparker is operated in the stationary mode the collapse of the bubble will occur near the anode inside the cathode tube causing the insulation and anode to erode faster. During discharge the inside wall of the cathode will experience high pressures which will ultimately cause it to "tear" away. This tearing is typically non-uniform and usually well below the top of the anode and insulation resulting in a significant deterioration on sparker performance. The addition of the fiberglass reinforcement eliminates this problem and allows the cathode to erode in a manner consistent with good sparker performance.

When the sparker is moving through the water at high speeds (15-30 knots) the bubble will move in back of the sparker (opposite the sparker travel). The turbulence created behind the sparker tends to hold the bubble against the backside of the sparker cathode where the collapse will impose large bending forces on the sparker. A "spine" structure, which incorporates a half section of copper tubing, is epoxied to the aft side of the cathode and covered with the fiberglass reinforcement. This provides additional rigidity to the sparker against these large bending forces at the end of the collar where the cathode exits and where the bending stresses will be highest. The location of the solder joint attaching the cathode tube to the collar is also important in this respect because the soldering process tends to weaken the cathode tube making it vulnerable to fatigue breakage. Past experiments have shown this to be a problem for joints made at the base of the collar where the bending stresses are highest. Making the soldering joint at the top of the cathode tube where it is flush with the collar inner surface minimizes this problem. The collapse of the bubble on the aft side of the sparker also causes additional (and significant) erosion of the cathode. The cathode wall must be thick enough to prevent the bubble from prematurely punching through the cathode wall and insulation to the anode. While this may not necessarily

alter the sparker performance it does effectively accelerate the erosion process. The addition of the half section of copper tubing on the aft side of the sparker provides the additional material needed to deter the punch through of the cathode from happening.

An important feature of this sparker design is the quick change out of the sparker/collar assembly. The stand pipe system is designed to allow the sparker/collar plus conductors assembly to be quickly removed from the standpipe in a few minutes. Additionally, the sparker/collar sub-assembly can be easily removed from the conductors and replaced either on the boat or in a workshop. A used sparker/collar can also be recycled in a facility with the proper machinery. This encompasses cutting off the cathode at the end of the collar and boring out the collar to the required size (.75 inches). A new cathode tube can then be soldered into place, and the remaining assembly outlined above steps carried out.

V. PERFORMANCE

The primary performance parameters of a sparker in this application is the lifetime (or erosion rate) and efficiency (acoustic energy radiated in a specific frequency band to the electrical energy stored in the capacitors). Both parameters depend on the discharge energy per pulse, repetition rate and speed of platform (flow rate past sparker). Due to the nature of the erosion process for this application, the erosion of the complete assembly must be considered. Since the operational time is critical to this application, the parameter that was measured was length of sparker eroded (cm) per hour. Usually the erosions of the electrodes and insulation were some what different thus the length taken was that of the shortest component. The following table lists the erosion data acquired at speeds, repetition rates and discharge energies consistent with those required for the mission effectiveness analysis done for the ALISS program. As indicated in the table, the erosion rate of the electrode is greater for the higher discharge energies which is expected. In additionally, note the increased erosion rates at lower speeds which is due to the bubble collapsing closer to the aft side of the electrode. Interestingly, using methodology developed by Donaldson [3] to predict erosion for an air discharge, the predicted erosion rate is close to that observed for the higher speeds.

Table 1. Sparker Erosion Rates

Energy/pulse kJoule	Rep. Rate Pulses/sec.	Plat. Speed knots	Erosion Cm/hr.
1	10	17	6.0
1	10	10	7.2
1	5	17	2.9
.5	10	17	3.0
.5	10	10	4.3

The efficiency of a sparker is strongly dependent on the pulse power system since it is part of the pulse power circuit. Some of the important parameters are: the energy discharged, the rise time of the pulse and the configuration of the sparker. Since the ALISS had rigorous goals not only in terms of output but also in terms of reliability and "time of operation without failure", the pulsed power/sparker system was not optimized for highest efficiency. The efficiencies for this system (sparker and pulsed power) were ~6% for the 1kJ energies and ~3% for the .5kJ discharges. These efficiencies are considered respectable compared to other systems that operate in this frequency range (20 – 5000Hz) especially given the constraints this system had to meet. Furthermore, when the pulse power system was modified for higher discharge rates (faster rise time) the efficiencies were considerably higher, >8% for the 1 kJ discharges. However, this configuration was not used for the pulsed power since the solid state switching components were operating near their upper limits where their reliability is marginal.

VI. CONCLUSION

A low cost, reliable and effective underwater sparker was developed for Navy applications in mine countermeasure systems. This system has been fully tested and successfully demonstrated in two major military exercises where the each sparker was normally operated over two hours without failure. However, further development of the sparker could be accomplished to enhance its performance. One concept that was investigated near the end of the program, was a horizontal orientation of the sparker with the water flow such that the bubble would be completely swept away from the sparker body. This should eliminate the erosion of the sparker due to the bubble collapse thus increasing its lifetime and facilitate consistent operation. Results from limited testing were promising but difficulties developed with keeping the sparker in the correct orientation which were caused by the high impulsive loads created by the sparker discharge.

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VII. REFERENCES

[1] Randy M. Roberts, "The Energy Partition of Underwater Sparks (U)," Applied Research Laboratories, The University of Texas at Austin, Austin TX, 29 June 1992.

[2] A. H. Olson and S. P. Sutton, "The physical Mechanisms Leading to Electrical Breakdown in Underwater Arc Sound Sources," J. Acoust. Soc. Am., (1993)

[3] Anthony L. Donaldson, *Electrode Erosion in High-Current, High-Energy Transient Arcs.*, Ann Arbor, MI: University Microfilms International, 1996